MODELING THE EFFECT OF REWORK TIMING: CASE STUDY OF A MECHANICAL CONTRACTOR

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ABSTRACT

Design and construction changes often cause rework, increase a project's cost, and delay its delivery. Data was obtained from a mechanical contractor in order to study rework timing and how it disrupts their detailing, fabrication, and installation processes. A set of simulation models illustrate the impact of rework timing. The focus is on early changes, that is, changes that become known when the contractor is detailing, so they can be dealt with either (1) right away during detailing, (2) during fabrication, or (3) during on-site installation. One model shows that dealing with changes in the detailing phase not only affects that phase but can have negative impacts on installation as well. Another model shows that detailing a project to a set of approved drawings and maintaining those until project completion, forces changes to be pushed downstream to site installation, which makes the impact of those changes more transparent to all players involved and can reduce negative iteration.

The question addressed in this paper is: When early changes occur, is there benefit to incorporating them during site installation instead of trying to capture, re-detail, and change drawings? Practitioners can use this research to assess resources to avoid rework.

KEY WORDS

changes, contracts, detailing, discrete event simulation, lean construction, mechanical contractor, rework

INTRODUCTION

Changes in a construction project not only cause rework but they also can lead to significant cost overruns and schedule delays. Changes stem from owner-modified project requirements, design errors, omissions, etc. (Love and Li 2000). Research has shown that if changes are identified and handled as early as possible, it will pay dividends in future work (Ibbs 2005). This idea also is grounded in lean production theory (i.e., it is akin to stopping the assembly line as soon as a quality defect has been detected, and fixing it right there and then). Change in design is known to be less costly than change in construction, however, change in design might be needed

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several times particularly when the corresponding costs are perceived to be minimal. Because certain changes and especially those in the course of construction tend to be costly, some owners prefer to not invoke them but instead complete their project as planned and immediately thereafter initiate a 'tenant improvement' project to handle the previously-identified changes.

In the case studied here, a mechanical contractor (a subcontractor to a general contractor) decided to allow changes to design drawings to be pushed down the line and dealt with during site installation instead of dealing with them in the detailing phase.

"We do it to ourselves by detailing too early … I can see when a project will require rework when we detail without complete information … We end up chasing our own tail trying to catch the numerous changes that occur."

Jim Mohar, personal communication, 15 September 2007

On one project, this contractor tried to catch all of the changes to drawings as soon as possible and determine the effect of those changes prior to fabrication and site installation of materials. However, they had to work hard to track down where the drawings were and what items were in fabrication vs. what items had been sent to the site for installation. In addition, they had to put in extra effort to ensure that the site installers had the most up-to-date drawings to work from.

"It is extremely difficult to get drawings out of the field once they are sent out because the field personnel make a lot of notes on them. I have to physically go to each of the sites and pull them out of the trailers."

Corina Heier, personal communication, 6 March 2008

This caused communication errors to occur and, ultimately, some incorrect items did get installed so that some site rework had to be accomplished anyway.

This case study discusses how early vs. late handling of changes can be modelled and reveals benefits of dealing with changes at the site. The benefits are (1) ease of more explicit accounting for costs incurred due to changes and (2) less negative iteration in the process.

LITERATURE REVIEW ON REWORK AND RELATED TOPICS

Change often leads to rework and rework is wasteful, by definition, if it can be eliminated without loss of value or causing failure to complete the project (Ballard 2000). Rework is classified as positive or negative. Positive rework adds value; an example is when designs are reworked and participants in the design process leave with a better understanding of customer requirements.

Informal surveys of design teams have revealed estimates as high as 50% of design time spent on needless rework (Ballard 2000). During the construction phase, rework extends project delivery and cost. Previous studies have found the cost of rework in design and construction to range from 2% to 12% of the contract cost (Josephson and Hammarlund 1999, Love and Li 2000). This is partly due to the variability in the execution of work.

Changes are identified as any variation from the original project scope (Ibbs 2005), they can either add or deduct from it. Changes can be the responsibility of the owner, the designer, the contractor, or a third party. When changes occur, they will affect a project differently based on whether they are dealt with early vs. late in the project. This defines the concept of changes timing.

The impact of changes on project delivery has been studied in different ways. Leonard et al. (1991) used 90 cases that resulted in owner/contractor disputes to quantify the effect of change orders on labor efficiency. Change order impacts were placed in three categories: (1) minor, (2) medium, and (3) high. Ibbs and Allen's (1995) CII report presented data from 89 cases to research three hypotheses. (1) Changes that occur late in a project are implemented less efficiently than those that occur early in a project. (2) The more change there is on a project, the greater its negative impact on labor productivity. (3) The hidden or unforeseeable costs of change increase with more project change. Hanna et al. (1999) looked at the loss of efficiency of labor productivity through four independent variables and presented a model to estimate the loss of efficiency. Ibbs (2005) studied the impact of changes on project productivity on early, normal, and late timing situations. He found that late changes impact project productivity more than early timing of changes. Therefore, if changes are needed at all, early changes should be encouraged and late changes discouraged. Isaac and Navon (2008) present a change control tool that identified the implication of change. The tool notifies stakeholders if the proposed change has the possibility of delaying the project.

Changes have a different impact depending on when they occur in a process. Presumably, changes occurring before the last responsible moment in design has been reached, will have less of a process impact than those same changes occurring later. The last responsible moment is defined as "the moment at which failing to make a decision eliminates an important alternative" (Poppendieck 2003). Thus, the mechanical contractor has to determine when the last responsible moment is to detail design drawings for fabrication and site installation.

Arbulu (2006) discussed a case study of producing rebar assemblies for a major transportation hub in the U.K. in which production was improved by synchronizing demand and supply, controlling work in process, and reducing the lead time for detailing, fabrication, assembly, delivery, and installation. This approach can be applied to the designing and making of mechanical components and assemblies as well. A pull system for detailing, fabrication and delivery of required items may improve performance when dealing with changes in the site.

Repenning and Sterman (2001) presented the idea that people do not get credit for correcting errors that never occur. This applies to the mechanical contractor who invests resources while trying to detail items that continue to change. The mechanical contractor does not get compensated for the detailing work that may have to occur multiple times (negative iteration) before the change is finalized.

Ford and Sterman (2003) describe the 90% syndrome: a project reaches about 90% completion on schedule but then stalls. This situation occurs in construction projects due to the multiple handoffs between the project players. Each player says they are on schedule yet may be behind—hoping to find time to correct errors—and delaying the release of more complete information.

This paper focuses on how a mechanical contractor deals with changes in construction of a healthcare facility that requires a state-agency building permit. These concepts of changes timing, last responsible moment, not getting credit for correcting errors that do not occur, and the 90% syndrome contribute to making project management of such facilities complex. To deal with this complexity the mechanical contractor implements the last responsible moment to detail changes. This last responsible moment is when the change is needed in site installation. Once the site installers are ready to implement the agreed upon change is when the upstream process of detailing and fabrication occurs. This reduces the amount of delay between processes and makes the cost of change more explicit.

DISCRETE EVENT SIMULATION (DES)

Discrete event simulation (DES) models help researchers study alternative production system configurations. These models, using for example the STROBOSCOPE (Martinez 1996) simulation engine, are made up of activities or processing steps (called 'Combis' = rectangles with cut-offs in the top-left corner, or Normals = rectangles), holding places for resources while they are not in use and thus accumulate (Queues), symbols to model flow (arrows) and stochastic or deterministic branching (Forks). These STROBOSCOPE elements have been integrated with a graphical interface in Microsoft Visio as a macro and allow construction of a variety of processes. STROBOSCOPE (1) Allows the state of the simulation to control the sequence of tasks and their relative priorities, (2) Models resource selection schemes so that they resemble the way resources are selected for tasks in actual operations, and (3) Models probabilistic material utilization, consumption and production.

A reason for selecting STROBOSCOPE is not only that the software is free to academic users but also that it is used by various other construction researchers, among whom these terms are known. This makes it easier for models to be replicated, evaluated, and experimented with by academic and industry peers. STROBOSCOPE has been used to model 'lean' applications such as 'pull' in pipe-spool supply and installation (Tommelein 1998), multi-tasking and batching in the delivery of pipe supports (Arbulu et al. 2002), feedback in planning, fabrication, shipping, and installation of duct work (Alves and Tommelein 2006), and various lean production management principles applied to high-rise apartment construction (Sacks et al. 2007).

DETAILING, FABRICATION, AND INSTALLATION DES MODEL

In California hospital construction, the Office of State-wide Health Planning and Development (OSHPD) is the agency that issues building permits. This agency ensures that hospitals meet a certain level of seismic performance, so that hospitals are likely to remain functional during and immediately following major catastrophes (specifically earthquakes). This permitting process often takes longer than a year to accomplish, which is detrimental to a hospital-owner's business plans. Therefore, in many situations, owners want to fast-track their project so construction can occur as soon as possible while other parts of the design still remain to be checked for quality. As a project is reviewed and if information is missing or errors are evident, the state agency returns the drawings to the design team for correction. In California hospital construction, this is known as a 'back-check.' Back-checks add time to final permitting and cause variation in the flow of information.

Figure 1 shows a flow diagram for a mechanical contractor from when it receives approved design drawings to final installation of product. Upstream pressure occurs because design drawings are due to the state agency for approval. As mentioned, this review process can be lengthy, therefore, to ensure drawings can be approved; the design engineers push to submit as early as possible. As a result, the design drawings may be not be adequate for permitting purposes, but even so, they may lack the required information for a contractor to fully detail the mechanical system. This results in the mechanical contractor receiving multiple sets of drawings which then have to be reworked to get the desired shop drawings for designer (architect and engineer or A&E) approval. The process in the dashed box can take up to 10 weeks, with each rework cycle adding three weeks to the process.

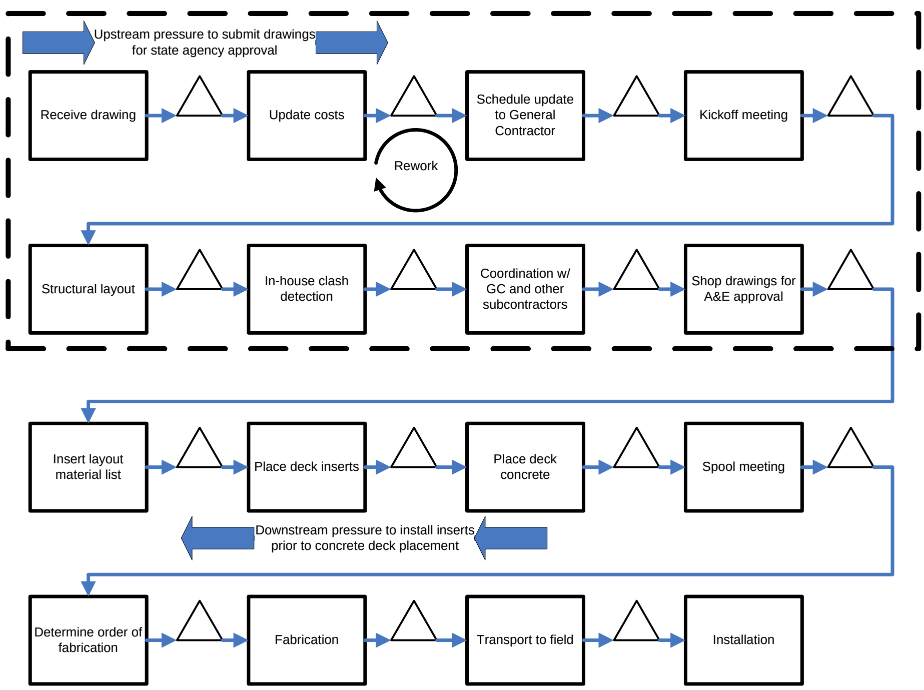

Figure 1: Flow diagram of mechanical contractor process

Downstream pressure on the mechanical contractor occurs from the general contractor's date to place concrete for the hospital floor slabs. The reason is that it is much more economical to drop inserts (straps from which duct will be hung) through metal decking before the concrete slab is cast over it, than to drill and secure strap into a hardened concrete slab, but this means that duct locations have to be locked in prior to concrete placing. From this date, the mechanical contractor typically tries to start the insert drawing four weeks in advance with the goal of having a complete insert drawing two weeks prior to deck placement. However, insert drawings cannot be completed until the layout of the mechanical system is finalized. If the layout continues to change, the insert drawings cannot be completed. These are the two main pressures that a mechanical contractor wrestles with throughout the project.

The model developed shows work that flows through three stages. First, the mechanical contractor details the required parts and pieces from the design drawings. This is an extensive effort to take single line design drawings and fill in three dimensional pipe and ductwork that shows all of the pieces needed for actual construction. This work has been facilitated by the use of computer renderings showing how pipe and ductwork is installed in a facility. For a large project, the mechanical contractor is responsible for coordinating the drawings with outside contractors, such as fire, life, safety, electrical and structural engineers.

Once the drawings have been coordinated, the materials can then be fabricated for site installation. This contractor uses in-house capabilities to produce the majority of project materials. Once fabricated, parts can be shipped and installed.

Site preparatory work must be completed prior to installation. In the example of ductwork, hangers and straps are inserted a few days prior to placement of concrete. However, the layout of the ductwork occurs many months prior to fabrication. During that time, design changes will invalidate existing layouts. In an effort to reduce rework, the mechanical contractor tries to detail the hangers and straps at the last responsible moment. Their goal is to have fully coordinated insert drawings two weeks prior to concrete placement. These inserts are then fabricated and installed 3-5 days prior to concrete placement. Once concrete is placed, if the layout changes, the mechanical contractor must drill into the concrete to place new hangers.

In each of the phases of work, changes can occur. In the detailing phase, many times, the mechanical engineer of record (i.e., the licensed engineer) is not done with their design, leaving gaps of information for which the detailers can not finalize. If the detailer has completed the drawings yet the mechanical engineer makes changes, then the drawings have to be re-detailed. This takes extra effort by the detailers to first interpret what the changes are and then determine how the drawings change. These changes can be small or large and may take time for the detailers to fully understand and capture all of the changes.

Changes can also occur in the fabrication phase when an item is in the midst of being made and changes to the original design are found. This requires the item to be re-detailed and re-fabricated. Changes can also be found when the item is on-site and the design changes, again, this requires the item to be re-detailed, re-fabricated and re-sent to the site. Figure 2 captures this situation in a discrete event simulation model.

As mentioned, within hospital construction, the permitting process may require the design engineers to complete a back-check by clarifying or correcting the design. However, the mechanical contractor, in an effort to expedite the process and meet the pressure of the concrete placement schedule, may detail from the original drawings and deal with the changes as they arise through each of the back-checks. This creates rework for the detailers, fabricators, and installers. The model simulates this scenario by allowing rework to occur at each of the phases.

Table 1 shows the input parameters used for an iteration of the model. It describes that there are 4,500 T (10,000 lbs) of material that must be completed. Rework has been set to zero percent, which means that as each piece of resource flows through the decision fork, none of the material will be required to be reworked. The model user can easily reset this parameter to study the impact of different degrees of rework. It is important to note that in this model, an item is only reworked once and then allowed to continue (a more complex model could be developed to include repeated cycling). The model allows you to input how many personnel are available to accomplish each stage of work in detailing, fabrication, and installation. It also allows you to determine how many workers are needed to accomplish each work package; in this scenario one worker is required at each stage. Finally, the model allows the user to vary the batch size at each stage. When batch size increases, the modeler must also change the time in each of the production activities, otherwise, it appears that workers can accomplish more work items per unit time.

Table 1: Model input parameters (no rework)

Original	Original Drawing Set	10000	FCrew	Number of fabricators available	1
ReworkDet	Percentage of Rework (Detailing)	0	FCrewReq	Fabrication Crew Required	1
ReworkFab	Percentage of Rework (Fabrication)	0	ICrew	Number of installers available	1
ReworkIns	Percentage of Rework (Installation)	0	ICrewReq	Install Crew Required	1
DCrew	Number of detailers available	1	FBatch	Fabricate batch size	1
DCrewReq	Detail Crew Required	1	DBatch	Detail batch size	1

In the detailing phase (figure 2), the first queue holds the total amount of material needed for the project. The work flows into a Combi called detailing and then one worker is drawn from a pool of workers and the item is detailed. The work then flows into a decision fork to determine if the item passes a quality check or has to be reworked. If the item passes, the work package flows into the able to fabricate queue. If it has to be reworked it flows into a Combi that draws from the available manpower and completes the rework.

This framework is replicated in the stages of fabrication and installation as shown in figure 2. However, items requiring rework in site installation have to be re-fabricated, so the item returns back to fabrication and once completed it is shipped back to the site for installation.

A line of balance chart shows the relative speeds of these sub-processes. Steep lines represent fast processes. Less steep lines represent slower processes. The horizontal distance between the top of a line to the bottom of the next line represents the relative delay to the start of the following process. Large distances represent longer delays while shorter ones represent processes that start right after each other.

Figure 3 shows a line of balance of the data collected from the model. It has four scenarios: (1) no rework (ideal situation), (2) 10% rework in each phase, (3) 20% rework in installation only, and (4) 30% rework in installation only. Scenarios (3) and (4) represent the paradigm of pushing changes to the installation phase.

In figure 3, detailing can occur rapidly if there are no changes to the design and the team is allowed to go through the entire set of drawings. Fabrication of items is also a steep line, because once requested, mechanical parts can be produced rapidly. This figure also shows that the detailing and fabrication phases could be delayed and do not affect the start of installation. Installation, however, is a less steep line in comparison to detailing and installation.

The concept the mechanical contractor implemented was to wait to work on the changes which reduced variation. The cost of rework, then, can be revealed through modelling as by the two vertical lines in figure 3. One line at 1,000 hours, the other at 1,150 hours, translate into dollars by multiplying the difference, 150 hours by an hourly labor rate. Assuming the man hour rate is 65 $/hr, the cost of change is $9,750.

TYPES OF CONTRACTS

Construction contracts play a major role in how people behave on projects. Changes can be a major source of funding to contractors and can significantly increase profits.

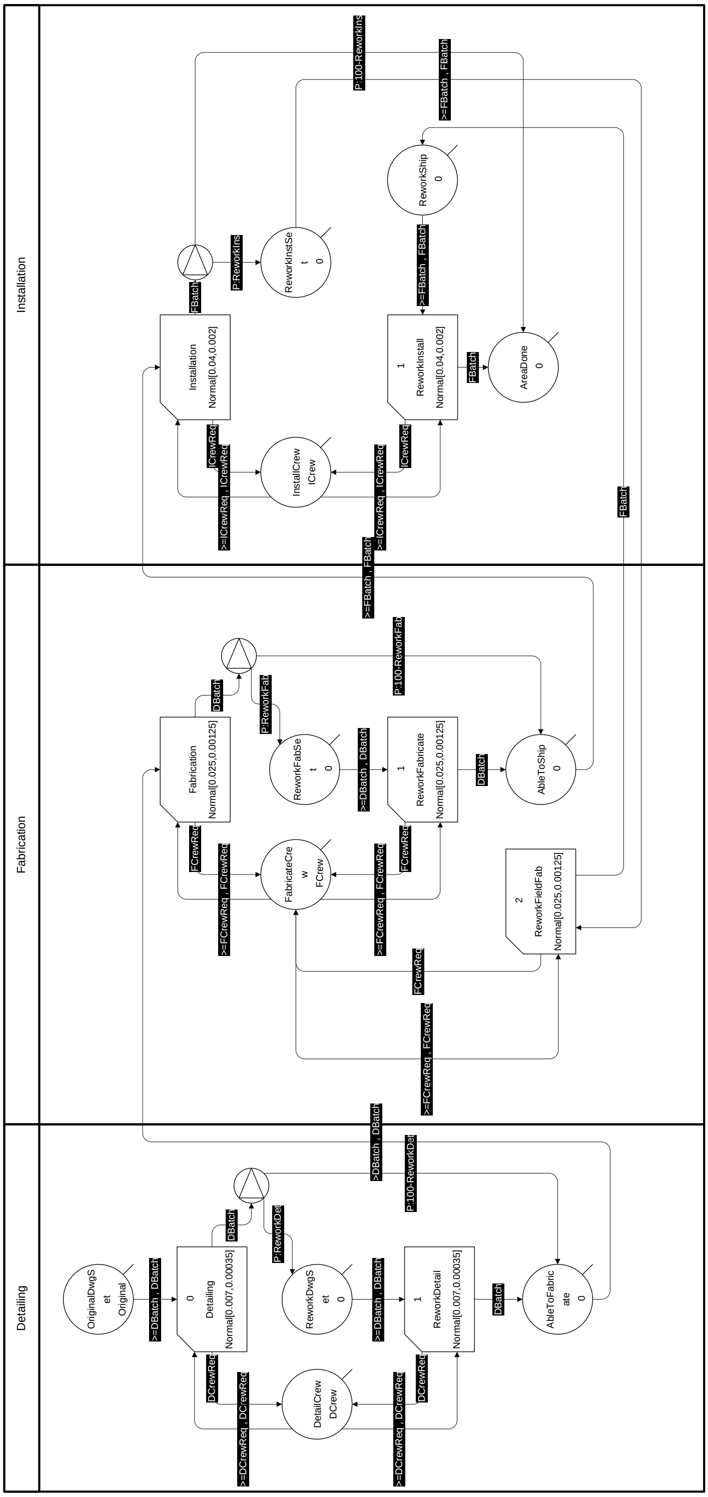

Figure 2: Discrete-event simulation of detailing, fabrication, and installation

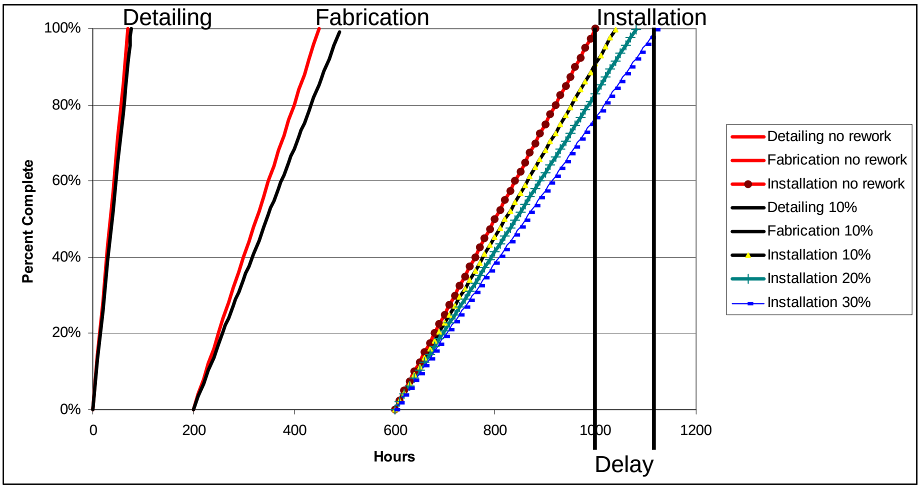

Figure 3: Line of balance for detailing, fabrication, and installation

Typically, changes are quantified by the total cost to install a new product. However, the full cost of the change may not be captured because it may not include the total time for a detailer to catch what the change is, to re-accomplish and de-conflict the drawings, and then re-fabricate the item. Owners do not pay for additional work a subcontractor does behind the scenes. This is the phenomenon of not getting credit for correcting errors that never happen (Repenning and Sterman 2001). However, by pushing changes to the site, the costs are more explicit and in some instances will be much higher than the owner is willing to pay for.

"By building to an agreed upon set of drawings, the cost of change becomes more transparent when the owner can physically see us replacing material with the change that they requested."

David Slane, personal communication, 6 March 2008

Therefore, with a traditional contract and risk-and-reward system in place, it is in the best interest of the mechanical contractor to delay dealing with the changes to site installation.

Contracts may offer incentives for subcontractors to reveal rework that occurs earlier, if they are reimbursed on a cost plus fee basis. A cost plus fee works by way of paying for the direct cost of the change and a set fee on top of the direct cost. It is then to the subcontractor's advantage to implement required changes sooner rather than later because they are assured compensation for that work.

SUMMARY

A discrete event simulation model was developed that begins to quantify process costs of rework in construction and highlights the need to improve process management on projects. This research shows that it can be more efficient to let changes occur at site installation and avoid them in the detailing and fabrication phases, especially when a traditional contract and risk-and-reward system are being used. In the absence of final design drawings, mechanical contractors can follow the process described in this paper as a way to reduce variation.

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